Dark Energy and Dark Matter, Mirror World and E$_6$ Unification

C.R. Das [1] [*]L.V. Laperashvili [2] [†],

[1] *Center for High Energy Physics, Peking University, Beijing, China*
[2] *The Institute of Theoretical and Experimental Physics, Moscow, Russia*

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Speaker - Larisa Laperashvili

[*] crdas@pku.edu.cn
[†] laper@itep.ru

Abstract

In the present talk we have developed a concept of parallel ordinary (O) and mirror (M) worlds. We have shown that in the case of a broken mirror parity (MP), the evolutions of fine structure constants in the O- and M-worlds are not identical. It is assumed that E_6-unification inspired by superstring theory restores the broken MP at the scale $\sim 10^{18}$ GeV, what unavoidably leads to the different E_6-breakdowns at this scale: $E_6 \rightarrow SO(10) \times U(1)_Z$ - in the O-world, and $E_6' \rightarrow SU(6)' \times SU(2)_Z'$ - in the M-world. Considering only asymptotically free theories, we have presented the running of all the inverse gauge constants α_i^{-1} in the one-loop approximation. Then a 'quintessence' scenario is discussed for the model of accelerating universe. Such a scenario is related with an axion ('acceleron') of a new gauge group $SU(2)_Z'$ which has a coupling constant g_Z extremely growing at the scale $\Lambda_Z \sim 10^{-3}$ eV.

Contents:

1   Introduction: Superstring theory and a mirror world.

The present investigation is based on the following corner stones of theory:

• Grand Unified Theories (GUTs) are inspired by the ultimate theory of superstrings, which gives the possibility of unifying all fundamental interactions including gravity:

M.B. Green, J.H. Schwarz and E. Witten, Superstring theory, Vol. 1,2, Cambridge University Press, Cambridge, 1988.

• There exists a mirror world, which is parallel to our ordinary world:

T.D. Lee and C.N. Yang, Phys.Rev. 104, 254 (1956);

I.Yu. Kobzarev, L.B. Okun and I.Ya. Pomeranchuk, Yad.Fiz. 3, 1154 (1966) [Sov.J.Nucl.Phys. 3, 837 (1966)].

• The mirror parity MP is broken:

"The only good parity ... is a broken parity!"

Z. Berezhiani, A. Dolgov and R.N. Mohapatra, Phys.Lett. B 375, 26 (1996);
Z. Berezhiani, Acta Phys.Pol. B 27, 1503 (1996);
Z.G. Berezhiani and R.N. Mohapatra, Phys.Rev. D 52, 6607 (1997).

Introduction: Superstring theory and a mirror world.

Superstring theory is a paramount candidate for the unification of all fundamental gauge interactions with gravity.

Superstrings are free of gravitational and Yang-Mills anomalies if a gauge group of symmetry is

$$\mathbf{SO(32)} \quad \text{or} \quad \mathbf{E_8 \times E_8}.$$

The 'heterotic' superstring theory $\mathbf{E_8 \times E_8'}$ was suggested as a more realistic model for unification:

D.J. Gross, J.A. Harvey, E. Martinec and R. Rohm,
Phys.Rev.Lett. 54, 502 (1985); Nucl.Phys. B256, 253 (1985).

M.B. Green, J.H. Schwarz and E. Witten,
Superstring theory, Vol. 1,2, Cambridge University Press, Cambridge, 1988.

This ten-dimensional Yang-Mills theory can undergo spontaneous compactification:

The integration over 6 compactified dimensions of the $\mathbf{E_8}$ superstring theory leads to the effective theory with the $\mathbf{E_6}$-unification in four-dimensional space.

Introduction: Superstring theory and a mirror world.

In the present investigation:

    See:

C.R. Das and L.V. Laperashvili, **Mirror World with Broken Mirror Parity,** E_6 **Unification and Cosmology,**

    to be published in Phys.Rev. D.

we consider the old concept:

there exists in Nature a 'mirror' (M) world (hidden sector) parallel to our ordinary (O) world.

This M-world is a mirror copy of the O-world and contains the same particles and their interactions as our visible world.

Observable elementary particles of our O-world have left-handed (V-A) weak interactions which violate P-parity. If a hidden mirror M-world exists, then mirror particles participate in the right-handed (V+A) weak interactions and have an opposite chirality.

Lee and Yang were first who suggested such a duplication of the worlds which restores the left-right symmetry of Nature:

T.D. Lee and C.N. Yang, **Phys.Rev. 104, 254 (1956);**

The term 'Mirror World' was introduced by Kobzarev, Okun and Pomeranchuk:

I.Yu. Kobzarev, L.B. Okun and I.Ya. Pomeranchuk, **Yad.Fiz. 3, 1154 (1966) [Sov.J.Nucl.Phys. 3, 837 (1966)].**

They have investigated a lot of phenomenological implications of such parallel worlds.

The idea of the existence of visible and mirror worlds became very attractive in connection with a superstring theory described by $\mathbf{E_8} \times \mathbf{E_8'}$.

2 Particle content in the ordinary and mirror worlds.

We can describe the ordinary and mirror worlds by a minimal symmetry

$$\mathbf{G_{SM} \times G'_{SM}}, \quad \text{where}$$

$$\mathbf{G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y}$$

stands for the Standard Model (SM) of observable particles: three generations of quarks and leptons and the Higgs boson. Then

$$\mathbf{G'_{SM} = SU(3)'_C \times SU(2)'_L \times U(1)'_Y}$$

is its mirror gauge counterpart having three generations of mirror quarks and leptons and the mirror Higgs boson.

The M-particles are singlets of $\mathbf{G_{SM}}$ and O-particles are singlets of $\mathbf{G'_{SM}}$.

These different O- and M-worlds are coupled only by gravity (or maybe other very weak interaction).

Including Higgs bosons ϕ we have the following SM content of the O-world:

$$\mathbf{L - set}: \quad (\mathbf{u, d, e}, \nu, \tilde{\mathbf{u}}, \tilde{\mathbf{d}}, \tilde{\mathbf{e}}, \tilde{\mathbf{N}})_{\mathbf{L}}, \phi_{\mathbf{u}}, \phi_{\mathbf{d}};$$

$$\mathbf{\tilde{R} - set}: \quad (\tilde{\mathbf{u}}, \tilde{\mathbf{d}}, \tilde{\mathbf{e}}, \tilde{\nu}, \mathbf{u, d, e, N})_{\mathbf{R}}, \tilde{\phi}_{\mathbf{u}}, \tilde{\phi}_{\mathbf{d}};$$

with antiparticle fields: $\tilde{\phi}_{\mathbf{u,d}} = \phi^*_{\mathbf{u,d}}, \;\; \tilde{\psi}_{\mathbf{R}} = \mathbf{C}\gamma_0\psi^*_{\mathbf{L}}$ and $\tilde{\psi}_{\mathbf{L}} = \mathbf{C}\gamma_0\psi^*_{\mathbf{R}}$.

Considering the minimal symmetry $\mathbf{G_{SM} \times G'_{SM}}$ we have the following particle content in the M-sector:

$$\mathbf{L' - set}: \quad (\mathbf{u', d', e'}, \nu', \tilde{\mathbf{u}}', \tilde{\mathbf{d}}', \tilde{\mathbf{e}}', \tilde{\mathbf{N}}')_{\mathbf{L}}, \phi'_{\mathbf{u}}, \phi'_{\mathbf{d}};$$

$$\mathbf{\tilde{R}' - set}: \quad (\tilde{\mathbf{u}}', \tilde{\mathbf{d}}', \tilde{\mathbf{e}}', \tilde{\nu}', \mathbf{u', d', e', N'})_{\mathbf{R}}, \tilde{\phi}'_{\mathbf{u}}, \tilde{\phi}'_{\mathbf{d}}.$$

In general, we can consider a supersymmetric theory when $\mathbf{G \times G'}$ contains grand unification groups: $\mathbf{SU(5) \times SU(5)'}$, $\mathbf{SO(10) \times SO(10)'}$, $\mathbf{E_6 \times E'_6}$, etc.

3   Gauge coupling constant evolutions in the O-world.

In the present paper we consider the running of all the gauge coupling constants in the SM and its extensions which is well described by the one-loop approximation of the renormalization group equations (RGEs) from the Electroweak (EW) scale up to the Planck scale.

For energy scale $\mu \geq \mathrm{M_{ren}}$, where $\mathrm{M_{ren}}$ is the renormalization scale, we have the following evolution for the inverse fine structure constants α_i^{-1} given by RGE in the one-loop approximation:

$$\alpha_i^{-1}(\mu) = \alpha_i^{-1}(\mathrm{M_{ren}}) + \frac{b_i}{2\pi}t,$$

where

$$\alpha_i = \frac{g_i^2}{4\pi},$$

g_i are gauge coupling constants and

$$t = \ln\left(\frac{\mu}{\mathrm{M_{ren}}}\right).$$

We have assumed that the following chain of symmetry groups exists in the ordinary world:

$$\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow [SU(3)_C \times SU(2)_L \times U(1)_Y]^{SUSY}}$$

$$\rightarrow \mathrm{SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z}$$

$$\rightarrow \mathrm{SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_Z}$$

$$\rightarrow \mathrm{SO(10) \times U(1)_Z \rightarrow E_6}.$$

3.1   Standard Model and Minimal Supersymmetric Standard Model.

We start with the SM in our ordinary world.

In the SM for energy scale $\mu \geq M_t$ (here M_t is the top quark pole mass) we have the following evolutions (RGEs) for the inverse fine structure constants α_i^{-1} (i = 1, 2, 3 correspond to the U(1), SU(2)$_L$ and SU(3)$_C$ groups of the SM):

C. Ford, D.R.T. Jones, P.W. Stephenson, M.B. Einhorn, **Nucl.Phys. B 395, 17 (1993),**

which are revised using updated experimental results:

C.R. Das, C.D. Froggatt, L.V. Laperashvili and H.B. Nielsen, **Mod.Phys.Lett. A 21, 1151 (2006)**

C.D. Froggatt, L.V. Laperashvili, H.B. Nielsen, **Phys.Atom.Nucl. 69, 67 (2006); Yad.Fiz. 69, 3 (2006).**

$$\alpha_1^{-1}(t) = 58.65 \pm 0.02 - \frac{41}{20\pi}t,$$

$$\alpha_2^{-1}(t) = 29.95 \pm 0.02 + \frac{19}{12\pi}t,$$

$$\alpha_3^{-1}(t) = 9.17 \pm 0.20 + \frac{7}{2\pi}t,$$

where

$$t = \ln\left(\frac{\mu}{M_t}\right).$$

We have used the central value of the top quark mass:

$$M_t \approx 174 \text{ GeV.}$$

Standard Model and Minimal Supersymmetric Standard Model.

The Minimal Supersymmetric Standard Model (MSSM)

(which extends the conventional SM)

gives the evolutions for α_i^{-1}

($i = 1, 2, 3$ for U(1), SU(2), SU(3) groups)

from the supersymmetric scale M_{SUSY} up to the seesaw scale M_R.

Figs. 1,3 present by red lines the SM and MSSM evolutions, which are given by the following MSSM slopes:

$$b_1 = -\frac{33}{5} = -6.6, \qquad b_2 = -1, \qquad b_3 = 3.$$

These evolutions are shown from M_t up to the scale M_{SUSY}, where

$$x = \log_{10}\mu \, (GeV), \quad t = x \cdot \ln 10 - \ln M_t.$$

In Figs. 1-4 we have presented examples with the following scales:

Fig. 1,2 $- 10$ TeV,
Fig. 3,4 $- 1$ TeV,

and

$$M_R \sim 10^{14} \text{ or } 10^{15} \text{ GeV}.$$

Here and below red lines correspond to the ordinary world.

3.2 Left-right symmetry, SO(10) and E_6-unification.

At the seesaw scale M_R the heavy right-handed neutrinos appear, and the following supersymmetric left-right symmetry originates:

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z.$$

Considering the running of coupling constants we have the following slopes:

$$b_X = b_1 = -6.6, \quad b_Z = -9, \quad b_3 = 3.$$

Also the running for $SU(2)_L \times SU(2)_R$ is given by the slope:

$$b_{22} = -2.$$

Then we have the following evolution:

$$\alpha_{22}^{-1}(\mu) = \alpha_{22}^{-1}(M_R) + \frac{1}{\pi} \ln \frac{\mu}{M_R},$$

with the following relation:

$$\alpha_{22}^{-1}(M_R) = \alpha_2^{-1}(M_R).$$

The next step is an assumption that the group by Pati and Salam originates at the scale M_4 giving the following extension of the group:

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z$$

$$\rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_Z.$$

J. Pati and A. Salam, **Phys.Rev. D 10, 275 (1974).**

The scale M_4 is given by the intersection of $SU(3)_C$ with $U(1)_X$:

$$\alpha_3^{-1}(M_4) = \alpha_X^{-1}(M_4).$$

Left-right symmetry, SO(10) and E$_6$-unification.

Considering only the minimal content of the scalar Higgs fields, we obtain the following slope for the running of $\alpha_4^{-1}(\mu)$:

$$b_4 = 5.$$

The intersection of $\alpha_4^{-1}(\mu)$ with the running of $\alpha_{22}^{-1}(\mu)$ leads to the scale M$_{\textbf{GUT}}$ of the SO(10)-unification:

$$SU(4)_C \times SU(2)_L \times SU(2)_R \rightarrow SO(10),$$

$$\alpha_4^{-1}(M_{GUT}) = \alpha_{22}^{-1}(M_{GUT}).$$

Then we deal with the running of the SO(10) inverse gauge constant $\alpha_{10}^{-1}(\mu)$, which runs from the scale M$_{\textbf{GUT}}$ up to the scale M$_{\textbf{SGUT}}$ of the super-unification E$_6$:

$$SO(10) \times U(1)_Z \rightarrow E_6.$$

The slope of this running is:

$$b_{10} = 1.$$

Then we have the following running:

$$\alpha_{10}^{-1}(\mu) = \alpha_{10}^{-1}(M_{GUT}) + \frac{1}{2\pi} \ln \frac{\mu}{M_{GUT}},$$

which is valid up to the M$_{\textbf{SGUT}}$ = M$_{\textbf{E6}} \sim 10^{18}$ GeV.

All evolutions of the corresponding fine structure constants are given in Figs. 1-4:

(O-world − red lines; M-world − blue lines).

Here Figs. 2 and 4 show the running of gauge coupling constants near the scale of the E$_6$-unification (for x $\geq$ 15).

4 Mirror world with broken mirror parity.

In general case the mirror parity MP is not conserved, and the ordinary and mirror worlds are not identical:

Z. Berezhiani, A. Dolgov and R.N. Mohapatra, **Phys.Lett. B 375, 26 (1996);**
Z. Berezhiani, **Acta Phys.Pol. B 27, 1503 (1996);**
Z.G. Berezhiani and R.N. Mohapatra, **Phys.Rev. D 52, 6607 (1997).**

If O- and M-sectors are described by the minimal symmetry group

$$\mathbf{G_{SM} \times G'_{SM}}$$

with the Higgs doublets ϕ and ϕ', respectively, then in the case of non-conserved MP the VEVs of ϕ and ϕ' are not identical: $\mathbf{v \neq v'}$.

Following Berezhiani-Dolgov-Mohapatra, we assume that

$$\mathbf{v' >> v}$$

and introduce the parameter characterizing the violation of MP:

$$\zeta = \frac{\mathbf{v'}}{\mathbf{v}} >> \mathbf{1}.$$

Then the masses of fermions and massive bosons in the mirror world are scaled up by the factor ζ:

$$\mathbf{m'_{q',l'} = \zeta m_{q,l}},$$

$$\mathbf{M'_{W',Z',\phi'} = \zeta M_{W,Z,\phi}},$$

but photons and gluons remain massless in both worlds.

Mirror world with broken mirror parity.

Let us consider now the following expressions:

$$\alpha_i^{-1}(\mu) = \frac{b_i}{2\pi} \ln \frac{\mu}{\Lambda_i}$$

— in the O-world, and

$$\alpha'^{-1}_i(\mu) = \frac{b'_i}{2\pi} \ln \frac{\mu}{\Lambda'_i}$$

— in the M-world.

A big difference between the Electroweak scales v and v′ will not cause a big difference between scales Λ_i and Λ'_i:

$$\Lambda'_i = \xi \Lambda_i \quad \text{with} \quad \xi > 1.$$

The values of ζ and ξ were estimated by astrophysical implications

(by Berezhiani-Dolgov-Mohapatra),

which gave:

$$\zeta \approx 30 \quad \text{and} \quad \xi \approx 1.5.$$

As for the neutrino masses, the same authors have shown that the theory with broken mirror parity leads to the following relations:

$$m'_\nu = \zeta^2 m_\nu,$$

$$M'_\nu = \zeta^2 M_\nu,$$

where m_ν are light left-handed and M_ν are heavy right-handed neutrino masses in the O-world, and m'_ν, M'_ν are the corresponding neutrino masses in the M-world.
The last relation gives the following relation for seesaw scales:

$$M'_R = \zeta^2 M_R.$$

4.1 Gauge coupling constant evolutions in the mirror SM and MSSM.

In the SM of the M-sector we have the following evolutions:

$$(\alpha')_i^{-1}(\mu) = (\alpha')_i^{-1}(M_t') + \frac{b_i}{2\pi}t' = \frac{b_i}{2\pi}\ln\frac{\mu}{\Lambda_i'},$$

where

$$(\alpha')_i^{-1}(M_t) = \alpha_i^{-1}(M_t) - \frac{b_i}{2\pi}\ln\xi,$$

or

$$(\alpha')_i^{-1}(M_t') = \alpha_i^{-1}(M_t).$$

In the M-world the scales Λ_i' are different with Λ_i, but O- and M-slopes are identical:

$$b_i' = b_i.$$

Finally, we obtain the following SM running of gauge coupling constants in the mirror world:

1)
$$(\alpha')_1^{-1}(\mu) = 58.65 \pm 0.02 - \frac{41}{20\pi}t',$$

2)
$$(\alpha')_2^{-1}(\mu) = 29.95 \pm 0.02 + \frac{19}{12\pi}t',$$

3)
$$(\alpha')_3^{-1}(\mu) = 9.17 \pm 0.20 + \frac{7}{2\pi}t',$$

where

$$t' = \ln\left(\frac{\mu}{M_t'}\right).$$

The pole mass of the mirror top quark is

$$M_t' = \zeta M_t.$$

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Gauge coupling constant evolutions in the mirror SM and MSSM.

If the Minimal Supersymmetric Standard Model (MSSM) extends the mirror SM , then mirror sparticle masses obey the following relation:

$$\widetilde{m}' = \zeta \widetilde{m},$$

and the mirror SUSY-breaking scale is larger:

$$M'_{SUSY} = \zeta M_{SUSY}.$$

The mirror MSSM gives the evolutions for $\alpha'^{-1}_i(\mu)$ $(i = 1, 2, 3)$ from the supersymmetric scale M'_{SUSY} up to the mirror GUT scale M'_{GUT}.

A seesaw scale M'_R in the M-world is given in the previous Subsection. For $\zeta = 3$:

$$M'_R = \zeta^2 M_R \approx 10^3 M_R.$$

Now if $M_R \sim 10^{14}$ GeV, then $M'_R \sim 10^{17}$ GeV, and a seesaw scale is close to the superGUT scale of the E_6-unification.

This means that mirror heavy right-handed neutrinos appear at the scale $\sim 10^{17}$ GeV.
Figs. 1-4 present by blue lines the mirror MSSM evolutions of $\alpha'^{-1}_i(\mu)$ $(i = 1, 2, 3)$.
In Figs. 1-4 we have presented (by blue lines) examples of the mirror MSSM evolutions with the scales

$$M'_{SUSY} = 10 \text{ TeV and } 300 \text{ TeV},$$

and $M'_R \sim 10^{17}$ GeV;
$\zeta = 10 -$ for $M_{SUSY} = 1$ TeV, and $\zeta = 30 -$ for $M_{SUSY} = 10$ TeV.

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4.2 Mirror gauge coupling constant evolutions

from SU(6) to the E$_6$-unification.

Let us consider now the extension of the MSSM in the mirror world.

The first step of such an extension is:

$$[SU(3)'_C \times SU(2)'_L \times U(1)'_Y]_{MSSM}$$

$$\rightarrow [SU(3)'_C \times SU(2)'_L \times U(1)'_X \times U(1)'_Z]_{MSSM},$$

and then

$$[SU(3)'_C \times SU(2)'_L \times U(1)'_X]_{MSSM}$$

$$\rightarrow SU(4)'_C \times SU(2)'_L.$$

Assuming that the supersymmetric group $SU(4)'_C \times SU(2)'_L$ originates at the scale M'_4, we find the intersection of $SU(3)'_C$ with $U(1)'_X$:

$$\alpha'^{-1}_3(M'_4) = \alpha^{-1}_X(M'_4).$$

The gauge symmetry group $SU(4)'_C$ starts from the scale M'_4 and runs up to the intersection with the evolution $(\alpha')^{-1}_2(\mu)$ corresponding to the supersymmetric group $SU(2)'_L$.

Here we have:

$$b_2 = -1.$$

The point of this intersection is the scale M'_{GUT}.

Mirror gauge coupling constant evolutions

from SU(6) to the E_6-unification.

The scale M'_{GUT} is given by the following relation:

$$(\alpha')_4^{-1}(M'_{GUT}) = (\alpha')_2^{-1}(M'_{GUT}).$$

At the mirror GUTscale M'_{GUT} we obtain the $SU(6)'$-unification if $U(1)'_Z$ also meets $SU(4)'_C$ and $SU(2)'_L$ at the same scale:

$$SU(4)'_C \times SU(2)'_L \times U(1)'_Z \to SU(6)'.$$

Here again

$$b_Z = -9.$$

Then we consider the running of $(\alpha')_6^{-1}(\mu)$ up to the superGUT scale $M'_{SGUT} = M'_{E6}$:

$$(\alpha')_6^{-1}(\mu) = (\alpha')_6^{-1}(M'_{GUT}) + \frac{11}{2\pi} \ln \frac{\mu}{M'_{GUT}},$$

where we have used the result

$$b_6 = 11.$$

Calculating the slope b_6, we assumed the existence of only minimal number of the Higgs fields, namely $h + \bar{h}$, belonging to the fundamental representation $\underline{6}$ of the $SU(6)'$ group.

Now it is obvious that we must find some unknown in the O-world symmetry group $SU(2)'_Z$, which must help us to get the desirable E'_6-unification in the M-world at the superGUT scale M'_{SGUT}:

$$SU(6)' \times SU(2)'_Z \to E'_6.$$

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Mirror gauge coupling constant evolutions

from SU(6) to the E_6-unification.

In the present investigation we assume that at the very small distances the mirror parity is restored and super-unifications E_6 and E_6', inspired by superstring theory, are identical having the same M_{SGUT}:

$$M_{SGUT}' = M_{SGUT} = M_{E6} \sim 10^{18} \text{ GeV}.$$

By this reason, the superGUT scale M_{SGUT} may be fixed by the intersection of the evolutions of gauge coupling constants in both – mirror and ordinary – worlds, which from the beginning were not identical.

The scale M_{SGUT} of the $E_6 \times E_6'$-unification is given by the following intersection:

$$\alpha_{10}^{-1}(M_{SGUT}) = (\alpha')_6^{-1}(M_{SGUT}).$$

Finally, one can envision the following symmetry breaking chain in the M-world:

$$E_6' \to SU(6)' \times SU(2)_Z'$$
$$\to SU(4)_C' \times SU(2)_L' \times SU(2)_Z' \times U(1)_Z'$$
$$\to SU(3)_C' \times SU(2)_L' \times SU(2)_Z' \times U(1)_X' \times U(1)_Z'$$
$$\to [SU(3)_C' \times SU(2)_L' \times U(1)_Y'] \times SU(2)_Z'.$$

Now it is quite necessary to understand if there exists the group $SU(2)_Z'$ in the mirror world.

What it could be?

5 A new mirror gauge group $SU(2)'_Z$.

The reason of our choice of the gauge group $SU(2)'_Z$:

See: *C.R. Das and L.V. Laperashvili,* **Mirror World with Broken Mirror Parity, E_6 Unification and Cosmology, submitted to Phys.Rev. D; ArXiv:**

was to obtain the correct running of $(\alpha')^{-1}_{2Z}(\mu)$, which:

- **leads to the new scale $\Lambda_Z \sim 10^{-3}$ eV at extremely low energies;**

See: *H. Goldberg,* **Phys.Lett. B 492, 153 (2000).**
P.Q. Hung, **Nucl.Phys. B 747, 55 (2006); J.Phys. A 40, 6871 (2007); arXiv: hep-ph/0707.2791.**
P.Q. Hung and P. Mosconi, **ArXiv: hep-ph/0611001.**

- **is consistent with the running of all inverse gauge coupling constants in the O- and M-worlds with broken mirror parity, considered in this investigation.**

Only the following slopes are consistent with our aims:

$$b_{2Z} = \frac{13}{3} \approx 4.33 \quad \text{and} \quad b_{2Z}^{SUSY} = 0.$$

5.1 Particle content of the $SU(2)'_Z$ gauge group.

The particle content of $SU(2)'_Z$ is as follows:

1. two doublets of fermions $\psi_i^{(Z)}$ and two doublets of the 'messenger' scalar fields $\phi_i^{(Z)}$ with $i = 1, 2$, or

2. one triplet of fermions $\psi_f^{(Z)}$ with $f = 1, 2, 3$, which are singlets under the SM, and two doublets of the 'messenger' scalar fields $\phi_i^{(Z)}$ with $i = 1, 2$.

3. We also consider a complex singlet scalar field: $\varphi_Z = (1, 1, 0, 1)$ under the symmetry group

$$G' = [SU(3)'_C \times SU(2)'_L \times U(1)'_Y] \times SU(2)'_Z.$$

Particle content of the $SU(2)'_Z$ gauge group.

The so called 'messenger' fields $\phi^{(Z)}$ carry quantum numbers of both the SM' and $SU(2)'_Z$ groups. They have Yukawa couplings with SM' leptons and fermions $\psi^{(Z)}$.

All the SM' and SM particles are assumed to be singlets under $SU(2)'_Z$. Then we obtain the following evolutions:

1. for the region $M'_t \leq \mu \leq M'_{SUSY}$:

$$\alpha'^{-1}_{2Z}(\mu) = \alpha'^{-1}_{2Z}(M'_t) + \frac{b_{2Z}}{2\pi} \ln \frac{\mu}{M'_t} \approx \frac{b_{2Z}}{2\pi} \ln \frac{\mu}{\Lambda_Z},$$

2. and for the region $M'_{SUSY} \leq \mu \leq M'_{SGUT}$:

$$\alpha'^{-1}_{2Z}(\mu) = \alpha'^{-1}_{2Z}(M'_{SUSY}) + \frac{b^{SUSY}_{2Z}}{2\pi} \ln \frac{\mu}{M'_{SUSY}}.$$

Also we have the following relation:

$$\alpha'^{-1}_{2Z}(M'_{SGUT} = M_{SGUT}) = \alpha^{-1}_{E6}.$$

In Figs. 1-4 we have shown the evolution $\alpha'^{-1}_{2Z}(\mu)$ given by blue lines for

$$b_{2Z} = \frac{13}{3}$$

and

$$b^{SUSY}_{2Z} = 0.$$

The total picture of the evolutions in the O- and M-worlds is presented simultaneously in Figs. 1–4 for the cases:

$M_{SUSY} = 1$ and 10 TeV, $M_R \sim 10^{14}, 10^{15}$ GeV, $M'_R \sim 10^{17}$ GeV, $\zeta = 10$ and $\zeta = 30$.

It is obvious that respectively $M'_{SUSY} = 10$ and 300 TeV.

Here $M_{SGUT} \approx 7 \cdot 10^{17}$ GeV and $\alpha^{-1}_{SGUT} \approx 27.64$

– for Figs. 1,2 ($M_{SUSY} = 10$ TeV),

$M_{SGUT} \approx 2.4 \cdot 10^{17}$ GeV and $\alpha^{-1}_{SGUT} \approx 26.06$

– for Figs. 3,4 ($M_{SUSY} = 1$ TeV).

Red lines correspond to the ordinary world, blue lines – to the mirror world.

5.2 The axion potential.

The Lagrangian corresponding to the group of symmetry

$$\mathbf{G'} = \mathbf{SU(3)'_C} \times \mathbf{SU(2)'_L} \times \mathbf{SU(2)'_Z} \times \mathbf{U(1)'_Y}$$

exhibits a $\mathbf{U(1)_A^{(Z)}}$ global symmetry.

The singlet complex scalar field $\varphi_{\mathbf{Z}}$ was introduced in theory with aim to reproduce the model of Peccei-Quinn (PQ) (well-known in QCD):

R. Peccei and H. Quinn, **Phys.Rev.Lett. 38, 1440 (1977).**

Then the potential:

$$\mathbf{V} = \frac{\lambda}{4}(\varphi_{\mathbf{Z}}^+\varphi_{\mathbf{Z}} - \mathbf{v_Z^2})^2$$

gives the VEV for $\varphi_{\mathbf{Z}}$:

$$< \varphi_{\mathbf{Z}} >= \mathbf{v_Z}.$$

Representing the field $\varphi_{\mathbf{Z}}$ as follows:

$$\varphi_{\mathbf{Z}} = \mathbf{v_Z}\exp(\mathbf{ia_Z/v_Z}) + \sigma_{\mathbf{Z}},$$

we obtain the following VEVs:

$$< \mathbf{a_Z} >=< \sigma_{\mathbf{Z}} >= \mathbf{0}.$$

A boson $\mathbf{a_Z}$ (the imaginary part of a singlet scalar field φ_Z) is an axion, and could be a massless Nambu-Goldstone (NG) boson if the $U(1)_A^{(Z)}$ symmetry is not spontaneously broken.

However, the spontaneous breakdown of the global $\mathbf{U(1)_A^{(Z)}}$ by $SU(2)'_Z$ instantons gives masses to fermions $\psi^{(Z)}$ and inverts $\mathbf{a_Z}$ into a pseudo Nambu-Goldstone boson (PNGB).

The axion potential.

Then the field $\varphi_{\mathbf{Z}}$ becomes:

$$\varphi_{\mathbf{Z}} = \exp(i\mathbf{a_Z}/\mathbf{v_Z})(\mathbf{v_Z} + \sigma(\mathbf{x})) \approx \mathbf{v_Z} + \sigma(\mathbf{x}) + i\mathbf{a_Z}(\mathbf{x}),$$

with the field σ is an <u>inflaton</u>.

Our axion $\mathbf{a_Z}(\mathbf{x})$ is just the famous PQ-axion with a mass squared

$$\mathbf{m_a^2} \sim \Lambda_{\mathbf{Z}}^3/\mathbf{v_Z} \sim 10^{-30} \ \mathbf{Gev^2},$$

and its potential, given by PQ model, has (for small $\mathbf{a_Z}$) the expression of the following type:

$$\mathbf{V}_{\text{axion}} \approx \frac{\lambda}{4}(\varphi_{\mathbf{Z}}^+ \varphi_{\mathbf{Z}} - \mathbf{v_Z^2})^2 + \mathbf{K}|\varphi| \cos(\mathbf{a_Z}/\mathbf{v_z}),$$

where $\mathbf{K}$ is a positive constant: $\mathbf{K} > 0$.

It is well-known that this potential exhibits two degenerate minima at $< \mathbf{a_Z} >= 0$ and $< \mathbf{a_Z} >= 2\pi\mathbf{v_Z}$ with the potential barrier existing between them.

The minimum of the above-mentioned potential at $< \mathbf{a_Z} >= 0$ corresponds to the 'true' vacuum, while the minimum at $< \mathbf{a_Z} >= 2\pi\mathbf{v_Z}$ is called the 'false' vacuum.

Such properties of the present axion leads to the 'quintessense' model of our expanding universe and the axion $\mathbf{a_Z}$ could be called an <u>acceleron</u>.

5.3   A new cosmological scale $\Lambda_Z \approx 3 \times 10^{-3}$ eV.

A new gauge group $SU(2)'_Z$ introduces a new dynamical scale $\Lambda_Z \sim 10^{-3}$ eV, which is consistent with present measurements of cosmological constant:

A.G. Riess et al., **Astron.J. 116, 1009 (1998); ArXiv: astro-ph/9805201.**
S.J. Perlmutter et al., **Nature 39, 51 (1998); Astrophys.J. 517, 565 (1999).**
C. Bennett et al., **ArXiv: astro-ph/0302207.**
D. Spergel et al., **ArXiv: astro-ph/0302209.**
P. Astier et al., **ArXiv: astro-ph/0510447.**
D. Spergel et al., **ArXiv: astro-ph/0603449.**

A total vacuum energy density of our universe (named cosmological constant) is equal to the following value:

$$\rho_{\text{vac}} \approx (3 \times 10^{-3} \text{ eV})^4.$$

A new asymptotically free gauge group $SU(2)'_Z$ gives the running of its inverse fine structure constant $(\alpha')^{-1}_{2Z}(\mu)$, which grows from the extremely low energy scale $\Lambda_Z \sim 10^{-3}$ eV up to the supersymmetric scale M_{SUSY} and then continues to run (in our model – does not change, see Figs. 1,2) up to the superGUT scale $M'_{\text{SGUT}} = M_{E6} \sim 10^{18}$ GeV.

Near the scale $\Lambda_Z \sim 10^{-3}$ eV the coupling constant of the gauge group $SU(2)'_Z$ infinitely grows. At this scale we have a minimum of the effective potential (the first vacuum in the mirror world).

Now it is worth the reader's attention to observe that in the mirror world we have three scales (presumably corresponding to the three vacua of the universe):

$$\Lambda_1 = \Lambda_Z \sim 10^{-12} \text{ GeV}, \quad \Lambda_2 = \Lambda_{\text{EW}} \sim 10^3 \text{ GeV},$$

$$\Lambda_3 = \Lambda_{\text{SGUT}} \sim 10^{18} \text{ GeV}.$$

They obey the following interesting relation:

$$\Lambda_1 \cdot \Lambda_3 \approx \Lambda_2^2.$$

6   The gauge group $SU(2)'_Z$ and the 'quintessence' model of our universe.

Recent models of the Dark Energy (DE) and Dark Matter (DM) are based on measurements in contemporary cosmology.

Supernovae observations at redshifts $(1.25 \leq z \leq 1.7)$ by the Supernovae Legacy Survey (SNLS), cosmic microwave background (CMB), cluster data and baryon acoustic oscillations by the Sloan Digital Sky Survey (SDSS) fit the equation of state for DE:

$$w = p/\rho$$

with a constant w:

$$w = -1.023 \pm 0.090 \pm 0.054.$$

which is given by

P. Astier et al., **ArXiv: astro-ph/0510447.**

The value $w = -1$ is consistent with the present quintessence model of accelerating universe dominated by a tiny cosmological constant and Cold Dark Matter (CDM):

P.J.E. Peebles and A. Vilenkin, **Phys.Rev. D 59, 063505 (1999),**
C. Wetterich, **Nucl.Phys. B 302, 668 (1998),**
L.J. Hall, Y. Nomura, S.J. Oliver, **Phys.Rev.Lett. 95, 141302 (2005); ArXiv: astro-ph/0503706.**

Here we present the quintessence scenario, which was developed in connection with the existence of a new gauge group $SU(2)'_Z$.

In our model a_Z plays the role of the 'acceleron', and a scalar boson σ_Z, partner of the acceleron, plays the role of the 'inflaton' in the low scale inflationary scenario.

6.1   Dark energy and cosmological constant.

For the ratios of densities $\Omega_X = \rho_X/\rho_c$, cosmological measurements gave:

$$\Omega_B \sim 4\%$$

for baryons (visible and dark),

$$\Omega_{DM} \sim 23\%$$

for non-baryonic DM, and

$$\Omega_{DE} \sim 73\%$$

for the mysterious DE, which is responsible for the acceleration of our universe.

We have considered that a cosmological constant (CC) is given by the value

$$CC = \rho_{vac} \approx (3 \times 10^{-3} \text{ eV})^4.$$

The main assumption is the following idea:

the universe is trapped in the false vacuum with $CC \neq 0$, but at the end it must decay into the true vacuum with vanishing CC.

The true Electroweak vacuum would have its vacuum energy density

$$CC = \rho_{vac} = 0.$$

Such a scenario exists in the model with Multiple Point Principle (MPP):

D.L. Bennett, H.B. Nielsen, Int.J.Mod.Phys. A 9, 5155 (1994); ibid., A 14, 3313 (1999).
See review: *C.R. Das, L.V. Laperashvili,* Int.J.Mod.Phys. A 20, 5911 (2005).

A non-zero (nevertheless tiny) CC would be associated only with a false vacuum.

Why CC is zero in a true vacuum?

<u>Dark energy and cosmological constant.</u>

People try to give a solution of this non-trivial problem:

C.D. Froggatt, L.V. Laperashvili, R.B. Nevzorov, H.B. Nielsen, in: Proceedings of 7th Workshop on 'What Comes Beyond the Standard Model', Bled, Slovenia, 19-30 Jul 2004 (DMFA, Zaloznistvo, Ljubljana, 2003), p.17; ArXiv: hep-ph/0411273.

L. Mersini, ArXiv: gr-qc/0609006.

The axion potential $V(a_Z)$ determines the origin of DE:

when the temperature of the universe T is high: $T >> \Lambda_Z$, then the axion potential is flat because the effects of the $SU(2)'_Z$ instantons are negligible for such temperatures.

When the temperature begins to decrease, the universe gets trapped in the false vacuum.

At $T \sim \Lambda_Z$ the true vacuum at $< a_Z >= 0$ has zero energy density (cosmological constant), and the barrier between vacua is higher.

The difference in energy density between the true and false vacua is now Λ_Z^4. The universe is still trapped in the false vacuum with $CC = \rho_{vac} = \Lambda_Z^4$.

The first order phase transition to the true vacuum is provoked by the bubble nucleation. In fact, the universe lives in the false vacuum for a very long time.

When the universe is trapped in the false vacuum at

$$< a_Z >= 2\pi v_Z,$$

the deceleration stops and acceleration begins at $\ddot{a}_Z = 0$,

then $\dot{a}_Z^2 = 0$ and $w(a_Z) = -1$.

The total energy density of the universe is dominated by the energy density of the false vacuum, and our universe undergoes an exponential expansion.

The universe trends to get the true vacuum, which has zero CC.

6.2 Dark matter.

The existence of DM (non-luminous and non-absorbing matter) in the universe is now well established.

Candidates for non-baryonic DM must be particles, which are stable on cosmological time scales. They must interact very weakly with electromagnetic radiation. Also they must have the right relic density.

These candidates can be black holes, axions, and weakly interacting massive particles (WIMPs). In supersymmetric models WIMP candidates are the lightest superparticles. The most known WIMP is the lightest neutralino. WIMPs could be photino, higgsino, or bino.

In our model fermions $\psi_i^{(\mathbf{Z})}$ of the gauge group $SU(2)'_{\mathbf{Z}}$ also could be considered as candidates for HDM (hot dark matter), and their composites ("hadrons" of $SU(2)_{\mathbf{Z}}$) could play a role of the WIMPs in CDM.

Investigating DM, it is possible to search and study various signals such as: $\psi^{(\mathbf{Z})} + e \to \psi^{(\mathbf{Z})} + e$, or $\psi^{(\mathbf{Z})} + N \to \psi^{(\mathbf{Z})} + N$, where e is an electron and N is a nucleon.

The detection of mirror particles: mirror quarks, leptons, Higgs bosons, etc., could be performed at future colliders such as LHC.

Also the 'messenger' scalar boson $\phi^{(Z)}$ can be produced at LHC, and then the decay: $\phi_i^{(Z)} \to \overline{\psi}_i^{(Z)} + l$, where l stands for the SM lepton, can be investigated with $\psi^{(\mathbf{Z})}$ as missing energies.

Leptogenesis and inflationary model also can be considered as implications of our new physics. The full investigation is beyond this paper.

7   <u>Conclusions.</u>

1. In this talk we have discussed cosmological implications of the parallel ordinary and mirror worlds with the broken mirror parity MP.

2. We have considered the parameter characterizing the breaking of MP, which is $\zeta = v'/v$, where v' and v are the VEVs of the Higgs bosons – Electroweak scales – in the M- and O-worlds, respectively.

3. During our numerical calculations, we have used the value $\zeta \approx 30$, in accordance with a cosmological estimate obtained by Berezhiani, Dolgov and Mohapatra.

4. We have assumed that at the very small distances there exists E_6-unification predicted by Superstring theory. We have chosen a theory, which leads to the asymptotically free E_6 unification, what is not always fulfilled.

5. We have shown that, as a result of the MP-breaking, the evolutions of fine structure constants in O- and M-worlds are not identical, and the extensions of the Standard Model in the ordinary and mirror worlds are quite different.

6. We have assumed that the E_6-unification, being the same in the O- and M-worlds, restores the broken mirror parity MP.

7. We have considered the following chain of symmetry groups in the ordinary world:

$$\mathbf{SU(3)_C \times SU(2)_L \times U(1)_Y}$$

$$\rightarrow \mathbf{SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z}$$

$$\rightarrow \mathbf{SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_Z \rightarrow SO(10) \times U(1)_Z \rightarrow E_6}.$$

<u>Conclusions.</u>

8. We have shown that a simple logic leads to the following chain in the mirror world:

$$SU(3)'_C \times SU(2)'_L \times SU(2)'_Z \times U(1)'_Y$$

$$\rightarrow SU(3)'_C \times SU(2)'_L \times SU(2)'_Z \times U(1)'_X \times U(1)'_Z$$

$$\rightarrow SU(4)'_C \times SU(2)'_L \times SU(2)'_Z \times U(1)'_Z$$

$$\rightarrow SU(6)' \times SU(2)'_Z \rightarrow E'_6.$$

9. The comparison of both evolutions in the ordinary and mirror worlds is given in Figs. 1–4, where we have presented the running of all fine structure constants. Here the SM (SM') is extended by MSSM (MSSM'), and we see different evolutions. Figs. 1,2 correspond to the SUSY breaking scales

$$M_{SUSY} = 10 \text{ TeV}, \quad M'_{SUSY} = 300 \text{ TeV},$$

while Figs. 3,4 are presented for

$$M_{SUSY} = 1 \text{ TeV}, \quad M'_{SUSY} = 10 \text{ TeV},$$

according to the MP-breaking parameter $\zeta \approx 30$ and 10. We have considered the value of seesaw scale in the O-world

$$M_R \sim 10^{14} \text{ GeV},$$

and in the M-world:

$$M'_R \sim 10^{17} \text{ GeV}.$$

10. It was shown that the (super)grand unification E'_6 in the mirror world is based on the group

$$E'_6 \supset SU(6)' \times SU(2)'_Z.$$

11. The presence of a new gauge group $SU(2)'_Z$ in the M-world gives significant consequences for cosmology: it explains the 'quintessence' model of our accelerating universe.

27

Conclusions.

12. We have presented in Figs. 1–4 the running of the $SU(2)'_Z$ gauge coupling by the evolution $\alpha'^{-1}_{2Z}(\mu)$, which takes its initial value at the superGUT scale

$$M_{SGUT} \sim 10^{18} \ GeV$$

and then runs down to very low energies, giving an extremely strong coupling constant at the scale $\Lambda_Z \sim 10^{-3} \ eV$.

13. We have discussed a 'quintessence' model of our universe: at the scale $\Lambda_Z \sim 10^{-3} \ eV$ instantons of the gauge group $SU(2)'_Z$ induce a potential for an axion-like scalar boson a_Z, which can be called "acceleron". The acceleron gives the value $w = -1$ and leads to the acceleration of our universe.

14. It was shown that the existence of the scale $\Lambda_Z \sim 10^{-3} \ eV$ explains the value of cosmological constant:

$$CC \approx (3 \times 10^{-3} \ eV)^4,$$

which is given by astrophysical measurements. Also recent measurements in cosmology fit the equation of state for DE: $w = p/\rho$ with a constant $w \approx -1$.

15. Following P.Q. Hung, we have assumed that at present time our universe exists in the 'false' vacuum given by the axion potential. The universe will live there for a long time and its CC (measured in cosmology) is tiny, but nonzero. However, at the end the universe will jump into the 'true' vacuum and will get a zero CC. But this problem is not trivially solved, and at present time we have only a hypothesis.

16. It was observed that the mirror world has three scales:

$$\Lambda_1 = \Lambda_Z \sim 10^{-12} \ GeV, \quad \Lambda_2 = \Lambda_{EW} \sim 10^3 \ GeV,$$

$$\Lambda_3 = \Lambda_{SGUT} \sim 10^{18} \ GeV.$$

They obey the following interesting relation:

$$\Lambda_1 \cdot \Lambda_3 \approx \Lambda_2^2.$$

Conclusions.

17. In our model of the universe with broken mirror parity we have obtained the following particle content of the group $SU(2)'_Z$:

    • two doublets of fermions $\psi_i^{(Z)}$ (i = 1, 2),
    or a triplet of fermions $\psi_f^{(Z)}$ (f = 1, 2, 3);

    • two doublets of scalar fields $\phi_i^{(Z)}$ (i = 1, 2).

18. Also, as H. Goldberg and P.Q. Hung, we have considered an existence of a complex singlet scalar field φ_Z, which produces "acceleron" a_Z and "inflaton" σ_Z and gives a 'quintessence' model of our universe with the low scale inflationary scenario.

19. Unfortunately, we cannot predict exactly the scales M_{SUSY} and M_R presented in our Figs. 1–4. The numerical description of the model depends on these scales. Nevertheless, we hope that a qualitative scenario for the evolution of our universe, developed in this paper, is valid.

20. We have discussed a possibility to consider the fermions $\psi_i^{(Z)}$ of the group $SU(2)'_Z$ as candidates for HDM and composites ("hadrons" of $SU(2)'_Z$) as WIMPs in CDM. Searching DM, it is possible to observe and study various signals of these particles.

21. Finally, it is necessary to emphasize that this investigation opens the possibility to fix a grand unification group (E_6 ?) from cosmology.

8   Acknowledgements

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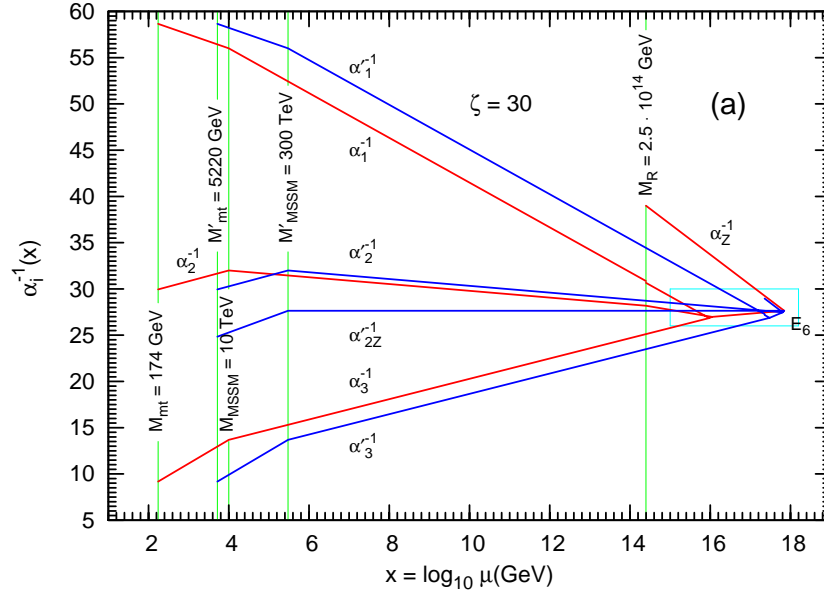[67] L. Mersini-Houghton, ArXiv: gr-qc/0609006.

Fig. 1: The running of the inverse coupling constants $\alpha_i^{-1}(x)$ in both ordinary and mirror worlds with broken mirror parity from the Standard Model up to the E_6 unification for SUSY breaking scales $M_{SUSY} = 10$ TeV, $M'_{SUSY} = 300$ TeV; $\zeta = 30$; and seesaw scales $M_R = 2.5 \cdot 10^{14}$ GeV, $M'_R = 2.25 \cdot 10^{17}$ GeV. This case gives: $M_{SGUT} \approx 7 \cdot 10^{17}$ GeV and $\alpha_{SGUT}^{-1} \approx 27.64$.
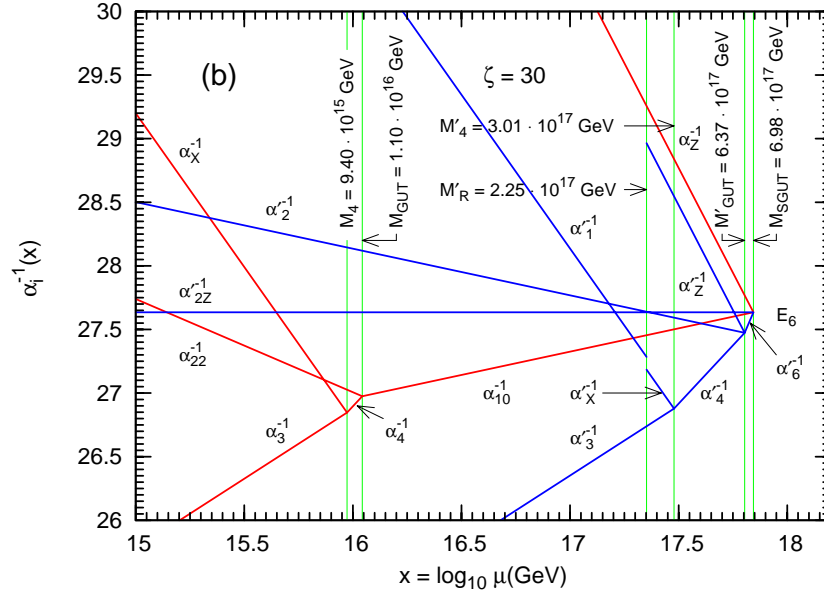

Fig. 2: This figure presents the same running of the inverse coupling constants $\alpha_i^{-1}(x)$ in both ordinary and mirror worlds from the scale 10^{15} GeV up to the E_6 unification for SUSY breaking scales $M_{SUSY} = 10$ TeV, $M'_{SUSY} = 300$ TeV; $\zeta = 30$; and seesaw scales $M_R = 2.5 \cdot 10^{14}$ GeV, $M'_R = 2,25 \cdot 10^{17}$ GeV; $M_{SGUT} \approx 7 \cdot 10^{17}$ GeV and $\alpha_{SGUT}^{-1} \approx 27.64$.
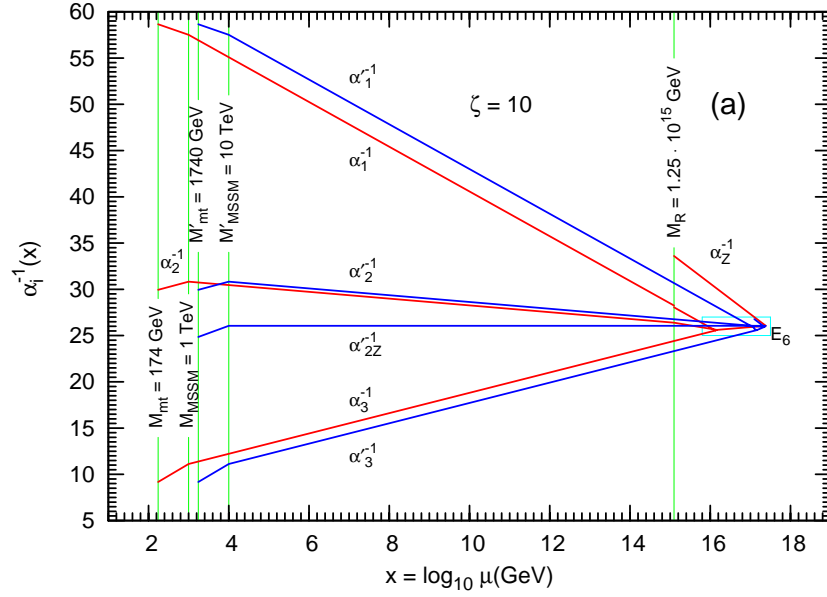
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Fig. 3: The running of the inverse coupling constants $\alpha_i^{-1}(x)$ in both ordinary and mirror worlds with broken mirror parity from the Standard Model up to the E_6 unification for SUSY breaking scales $M_{SUSY} = 1$ TeV, $M'_{SUSY} = 10$ Te; $\zeta = 10$; and seesaw scales $M_R = 1.25 \cdot 10^{15}$ GeV, $M'_R = 1.44 \cdot 10^{17}$ GeV. This case gives: $M_{SGUT} \approx 2.4 \cdot 10^{17}$ GeV and $\alpha_{SGUT}^{-1} \approx 26.06$.
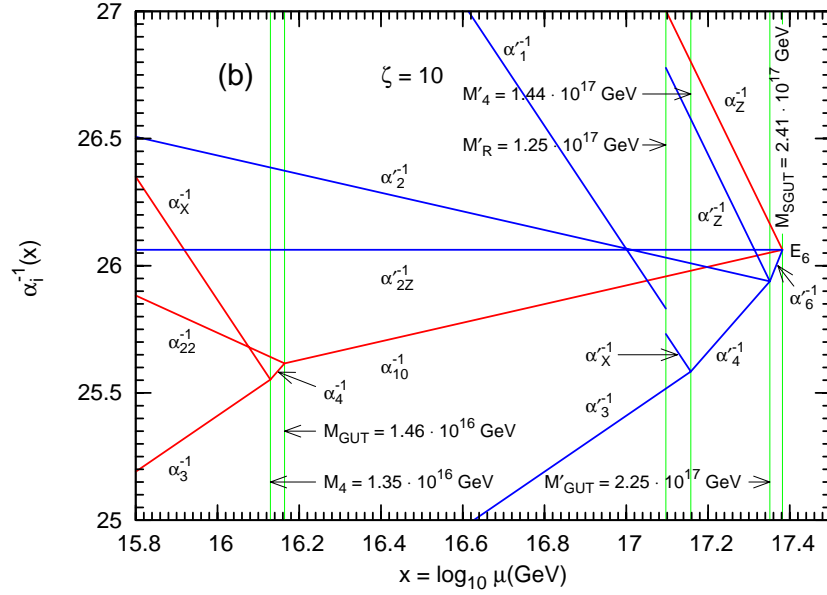

Fig. 4: This figure presents the same running of the inverse coupling constants $\alpha_i^{-1}(x)$ in both ordinary and mirror worlds with broken mirror parity from the scale 10^{16} GeV up to the E_6 unification for SUSY breaking scales $M_{SUSY} = 1$ TeV, $M'_{SUSY} = 10$ TeV; $\zeta = 10$; and seesaw scales $M_R = 1.25 \cdot 10^{15}$ GeV, $M'_R = 1.44 \cdot 10^{17}$ GeV; $M_{SGUT} \approx 2.4 \cdot 10^{17}$ GeV and $\alpha_{SGUT}^{-1} \approx 26.06$.